SOIL DEGRADATION

November 2021

True pricing method for agri-food products

Soil degradation

Impact-specific module for true price assessment

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[4] For more information on the *PPS True and Fair Price for Sustainable Products*, please refer to https://www.wur.nl/nl/project/Echte-en-eerlijke-prijs-voor-duurzame-producten.htm

Relation to other components of the true price methodology for agri-food products

*This **Soil degradation - Impact-specific module for true price assessment** was developed by True Price and Wageningen Economic Research within the PPS True and Fair Price for Sustainable Products.*

This document contains the key methodological aspects to measure and value one impact of agri-food products and value chains: soil degradation.

*This impact-specific module is complemented by five other **Natural capital modules** and seven **Social and human capital modules**. The other natural capital modules are: 1) Contribution to climate change; 2) Land use, land use change, biodiversity and ecosystem services; 3) Air, soil and water pollution; 4) Scarce water use; 5) Fossil fuel and other non-renewable material depletion. These impact-specific modules are preceded by the **Valuation framework for true pricing of agri-food products**, which contains the theoretical framework, normative foundations and valuation guidelines, and the **Assessment Method for True Pricing of Agri-Food products**, which contains modelling guidance and requirements for scoping, data and reporting (Figure 1).*

Together, these documents present a method that can be used for true pricing of agri-food products, and potentially other products as well.

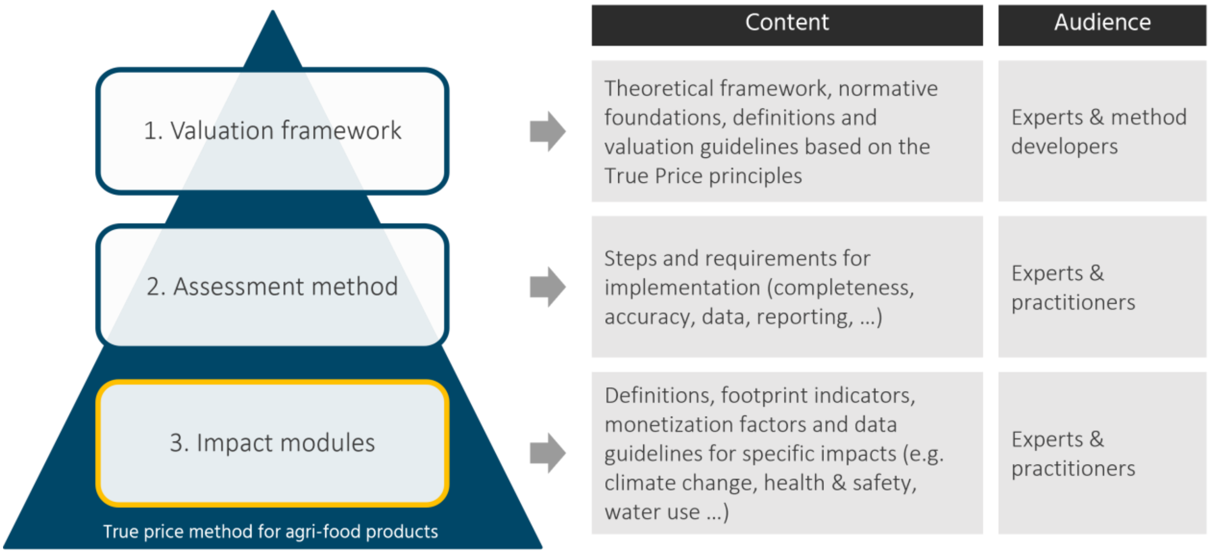

Figure 1: Components of the true price methodology for agri-food products. This document is one of the impact modules.

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1. Introduction

This document provides a method module for the assessment of the true price of an agricultural or horticultural product, within the public-private partnership 'Echte en Eerlijke Prijs'. It contains the key methodological aspects to measure and value one impact of agri-food products and value chains: soil degradation.

This module must be used together with the **True Pricing Assessment Method for Agri-food Products** (Galgani et al, 2021a). As for other impacts in true pricing, this methodology is compatible with Life Cycle Assessment (LCA).

This document consists of eight sections. Section 2 provides the key definitions. Section 3 provides background information and the rationale for including the impact of soil degradation as part of the true price. Section 4 offers guidance for scoping and determining materiality within a true price assessment. Section 5 presents the footprint indicators of the impact and Section 6 the modelling approach. Section 7 provides the monetisation approach. Finally, Section 8 provides an overview of key items for further research. In addition, a glossary of key terms and annexes with additional information are provided at the end of the document.

2. Definitions

Soil degradation is an environmental impact of agri-food products and it is defined as follows:

- **Soil degradation** is defined as the physical, chemical and biological decline in soil quality driven by productive activities, like excessive use of irrigation or unbalanced use of fertilisers, and it can manifest itself in multiple ways, for example as loss of nutrients, loss of organic matter, increased soil erosion (from water or wind), soil compaction, waterlogging and salinisation (Lal, 2009). **Soil quality** is the capacity of a soil to have the desired soil functions sufficiently available under varying conditions for a combination of objectives such as food production, an efficient nutrient cycle, and the preservation of biodiversity (Hanegraaf et al., 2019).

In this module three indicators are used for the quantification of soil degradation:

- **Soil erosion** is a natural process in which factors such as water, wind and gravity erode soil. Natural soil erosion is generally not problematic for soil fertility/quality, but due to various human activities that are accelerating this process it has become so. Examples of such activities are deforestation, overgrazing, construction activities and various (and varying) forms of agriculture (Osman, 2014). The consequences of soil erosion can be classified as on-site and off-site. On-site consequences include amongst other things the loss of fertile soil. Off-site consequences include amongst other things the salinisation of reservoirs and eutrophication of stagnant waters.
- **Soil organic carbon (SOC)** refers to the carbon content of soil organic matter (SOM). SOM is all material in the soil that is produced by living organisms (plants or animals) and ends up in the soil through decomposition (Bot, 2005). Most productive agricultural soils have between 3 and 6% organic matter (Cornell University Cooperative Extension, 2008). Soil organic matter consists of material in various phases of decomposition, which in turn contains between 45 and 60% SOC. SOC is essential for various functions and ecosystem services in which soil plays an integral role. In most soil types, reductions in SOC, for example due to intensive tillage, the use of artificial fertilisers, or irrigation can affect, among other things, soil fertility, biodiversity and the amount of substances that leak into groundwater (Garrigues et al., 2012). Some soil types are an exception, for example peat meadow. These soil types have such a high SOC content, that a (small) decline

does not lead to (negative) effects. When land is converted, SOC contained in the soil is also emitted into the atmosphere, mainly as CO_2, where it contributes to climate change. Different farming practices can accelerate or reverse this process.

- **Soil compaction** is defined as a decrease in soil volume and/or a change in soil form that affects the soil pore functions (RECARE & EC, 2016). Compaction hinders the aeration of the soil, affecting the rooting density and depth, and disturbing plant growth. Moreover, compaction diminishes the capacity of soil to infiltrate water, resulting in an increased volume of surface runoff (Görlach et al., 2004). Compaction occurs in the top and sub soil, naturally, through trampling of animals, or by the use of agricultural machinery (Stolte et al., 2016). Compaction of the topsoil has a significant impact on crop yield, and compaction of the subsoil (the layers below the tillage depth) affects a range of soil ecosystem services, including crop yield. Subsoil compaction is characterised as particularly problematic, as the effects on the soil are '*invisible, cumulative and persistent*' (RECARE & EC, 2016). Off-site consequences of soil compaction include a higher risk of flooding and water pollution (Görlach et al., 2004).

Relation of soil degradation to other impacts in true pricing

Soil degradation is related to other impacts within true pricing, namely soil, water and air pollution, climate change contribution, and land use and biodiversity. Soil pollution is defined as eco- and human toxicity caused by emissions to soil. Soil pollution occurs due to the runoff and discharge of contaminants, for example heavy metals (Huijbregts et al., 2016). It is in principle a form of soil degradation but is added separately to be consistent with the air and water pollution impacts, which follow an LCA approach. Water pollution is defined as emissions to water contributing to ecotoxicity and human toxicity, as well as eutrophication of marine- and freshwater. Water pollution occurs due to the runoff and discharge of nutrients to marine and freshwater bodies and the subsequent rise in nutrient levels.

The impact of contribution to climate change is defined as the contribution to climate change from emissions of greenhouse gases (GHG), while air pollution is defined as impacts caused by emissions to air other than climate change. These include ozone layer depletion, acidification, photochemical oxidant formation, particulate matter formation, terrestrial eutrophication from emissions to air, terrestrial and aquatic ecotoxicity and human toxicity from toxic emissions to air. Climate change and air pollution relate to soil degradation through the increased fertiliser use to recover for the lost soil fertility.

In true price assessments, soil degradation is specified separately from land use and biodiversity. In the true price method, land use refers to the combination of two Natural Capital impacts, land use and land use change. Land use change is defined as the change in land-cover that can affect ecosystem services and the climate system, while land use entails the decreased availability of land for purposes other than the present one. In true pricing, biodiversity, alongside ecosystem services, is not quantified as a separate Natural Capital impact, but through land use. Soil degradation focusses solely on the effects on soil. Soil degradation could in theory be considered a sub-impact of land use since soil fertility is an ecosystem service. Soil Organic Carbon (SOC) loss, for example, is considered an indicator of land transformation[5] in the PEF methodology (European Commission, 2013). However, for clarity of reporting, soil degradation is in this method considered a separate impact.

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[5] Land transformation in PEF considers the extent of changes in soil carbon in land properties and the area affected (changes in quality multiplied by the area) (European Commission, 2013).

3. Background and rationale for including these impacts as part of the true price

The **Valuation Framework for True Price Assessment of Agri-food Products** (Galgani et al., 2021b) contains the guiding principle to include impacts in true pricing when there is a link with internationally defined rights or conventions. Soil degradation is linked to *the right to a safe, clean, healthy and sustainable environment* and *the right to have access to the natural resources of the earth (for future generations)*. This is in line with international agreements such as *Our Common Future* (Brundtland, 1987) and the *Sustainable Development Goals* (UN, 2015).

Private and societal costs

True pricing entails the quantification and valuation of external effects. Soil degradation, which happens on private land, is only an external effect, or a societal cost, to a limited degree. Parts of the costs deriving from soil degradation are private costs borne by the landowner or land manager, the farmer.

Some aspects of soil degradation on private land should not be seen as an externality, because these are reflected in the price of the output. When soil degrades, it becomes less valuable. Similarly, a degraded soil will require more inputs and therefore lead to higher costs and a lower income to the farmer. These costs are private costs and land prices, therefore, should provide private incentives for soil degradation control (Ervin, 1985; Telles et al., 2011). This is effectively '*welfare enhancing*': soil management practices structure land as an economic resource in such a way that it maximises the total utility received by all individuals – e.g., consumers get access to (better) agricultural products, farmers get paid for their efforts, and so on.

On the other hand, important effects of soil degradation are external, because they are not reflected in the price of output or because they are borne by others. Therefore, soil degradation is a societal cost and should be included in the true price because of the following reasons:

- On a large scale, loss of soil quality that is irreversible or very costly to reverse can affect food security of future generations. Halting land degradation is in fact part of SDG 15 (UN, 2015, see Annex F).
- Soil degradation leads to other negative effects on biodiversity and landscape diversity, and it increases nutrient runoff.

Because of its external effects, or societal costs, economic actors[6] are considered to have a responsibility to limit soil degradation on all land, both privately and collectively owned.

In practice, separating private and external, or societal, costs is complex. Reduced yields have a link to food security also for present generations (Lankoski & Ollikainen, 2003; Lal, 2009). Also, poverty, imperfect capital markets or insecure land tenure in practice can lead to the fact that land prices are not influenced by soil quality. As a result, even traditionally internal effects have external components.

The general principle to be applied is that only societal effects should be included. In practice this is difficult to do entirely, but whenever possible this is done. For example, in the case of soil compaction, only effects on deeper layers of subsoil are considered as external costs, as these are the ones which are expected to have long-term irreversible effects (Stoessel et al., 2018), and therefore lead to costs for other stakeholders than the landowner. However, when valuing SOC loss or soil erosion, it is not possible to differentiate easily

[6] Responsibility is not only attributed to businesses, but to all market actors (businesses, consumers, investors, governments).

between private and societal costs, so some degree of private costs may also be part of the monetisation factors. Further research is needed to separate private costs of soil degradation from external effects for the purpose of true pricing.

4. Guidance for the scoping phase of a true price assessment

In the scoping phase of a true price assessment, the researcher should identify all relevant processes in the life cycle of the product (or steps in its value chain). This involves assessing which intermediate products are produced and what inputs are required. After that, it should be determined which impact must be quantified for each process in the life cycle – a so-called materiality assessment - by identifying all relevant processes that are expected to contribute more significantly to the total impact. This helps the analysis as it focusses attention on these processes in subsequent steps. This process is explained in the **True Pricing Assessment Method for Agri-food Products** (Galgani et al., 2021a).

All agricultural processes that involve cultivation of crops in soil or grazing cattle are potentially material when assessing soil degradation. Materiality should be assessed for each indicator separately (soil loss from water erosion, soil loss from wind erosion, soil compaction, SOC loss). SOC loss can be easily calculated for any value chain using the IPCC method. The soil compaction method provided here is only applicable to arable land.

5. Footprint Indicators

There are many potentially relevant indicators for determining soil degradation (van den Elsen et al., 2019). A complete measurement of soil degradation with all indicators is infeasible and expensive for most practitioners that aim to calculate the true price of a product (of which soil degradation can be an element).

In this module soil degradation is measured using three footprint indicators presented in Table 1: soil erosion, soil organic carbon loss and soil compaction. Quantification is done either by primary measurement (which is more accurate but more time consuming), by using results from publicly available studies or by modelling as explained in Section 6. The indicator SOC loss corresponds to the impact category Land Use in the PEF method for Life Cycle Assessment (LCA).

Table 1: Overview of footprint indicators

Footprint indicators	Footprint sub-indicators	Unit	Suggested modelling approach
Soil Erosion	Soil loss from water erosion	kg soil lost	RUSLE model (ESDAC, n.d.a)
	Soil loss from wind erosion	kg soil lost	RWEQ model (ESDAC, n.d.b)
Soil Organic Carbon (SOC) Loss		kg SOC	Difference in C-stocks (Ogle et al., 2019a)
Soil Compaction	Driving intensity	(corrected) ton-km	Stoessel et al. (2018)

6. Modelling Approach

6.1. Soil Erosion

Soil erosion due to water is quantified using the RUSLE model. Soil erosion due to wind is quantified using the RWEQ model.

Soil erosion due to water: the RUSLE model

The footprint indicator of soil erosion can be calculated with the Revised Universal Soil Loss Equation (RUSLE) for soil erosion by *water.* A RUSLE model determines the expected average annual erosion per hectare (E in t.ha^{-1}.yr^{-1}) as a multiplication of five parameters: erosive force of rainfall (R in MJ.mm.ha^{-1}.h^{-1}.yr^{-1}), the extent to which the type of soil erodes (K in t.ha.h.ha^{-1}.MJ^{-1}.mm^{-1}), the length and steepness of the slope of the area over which erosion is calculated (LS, dimensionless), the way in which the soil is used (C, dimensionless), and the extent to which precautions against erosion are taken (P, dimensionless) (ESDAC, n.d.a):

(1) $$E = R * K * C * LS * P$$

Wherever possible, the parameters must be determined with location-specific values. When this is not possible, (regional) proxies can be used with the same characteristics (soil type, agricultural system, climate, slope, etc.). If there are several locations with different types of climate, soil and agricultural systems in a single value chain step, it is preferable to calculate E separately for each location and to use the weighted average of separate calculations. If this is not possible, representative averages of the individual parameters (R, K, C, LS, and P) can be used.

Soil erosion due to wind

Soil also erodes by exposure to wind. In fact, due to the inclusion of 'steepness of slope' in the RUSLE model water erosion is negligible in relatively flat countries, such as the Netherlands (Panagos et al., 2012). Wind erosion does play a role on Dutch arable land (Borrelli et al., 2017). Quantification of the footprint indicator soil erosion by *wind*, can be realised through existing research. For studies that provide values for wind erosion on the region or crop of interest, these values can be directly used.

If such studies are not available, but the impact is still described as material in the literature, an appropriate model to quantify wind erosion should be used. The Revised Wind Erosion Equation (RWEQ) model as described in Fryrear et al. (1999) and ESDAC (n.d.b) is an example of how soil erosion by wind can be quantified. This model predicts the amount of soil erosion from a given area in a given time period, due to wind.[7] This model requires specific input data, such as a weather factor, soil erodible fraction, soil crust factor, soil roughness and a combined crop factor, in order to estimate the soil loss per hectare per year (Borelli et al., 2017). Borelli et al. (2017) made a GIS version of the model and they have available data on soil loss due to wind erosion in EU for 2016. These data are given in a GeoTIFF raster format.

The loss of soil per hectare per year should then be converted to soil loss per functional unit of the study (e.g., 1 kg of produce) dividing by the annual yield per hectare.

6.2. Soil Organic Carbon (SOC) Loss

This section defines the quantification model for the footprint indicator SOC loss with existing SOC measurements. If these are not available, they can be modelled using the IPCC method (Ogle et al., 2019a; Ogle et al., 2019b, Tier 1 or Tier 2), described in Annex B.

Difference in carbon stocks

[7] The researcher should be aware of potential overlap between water- and wind erosion, in order to avoid double counting.

The footprint indicator loss of SOC is the difference in carbon (C) stocks per hectare at 30 centimetres depth between the beginning and the end of a production year. Because the change in SOC is a slow process, the annual change of carbon stock is estimated based on the difference in carbon stock over a longer period of time:

(2) $$SOC_{loss} = \frac{SOC_0 - SOC_{0-T}}{T}$$

Where SOC_{loss} is the loss of soil organic carbon (in tonnes $C.ha^{-1}.yr^{-1}$), SOC_0 is the soil organic carbon stock (in tonnes $C.ha^{-1}$) at the end of the inventory period, SOC_{0-T} is the soil organic carbon stock (in tonnes $C.ha^{-1}$) at the beginning of the inventory period and T equals 20 years[8]. Because true pricing identifies the negative externalities of a product, only SOC losses are considered. If the amount of SOC in the soil has increased since the reference period, SOC loss is 0.

The loss of SOC per hectare per year should then be converted to SOC loss per functional unit of the study (e.g., 1 kg of produce) dividing by the annual yield per hectare.

6.3. Soil Compaction

The quantification model for the footprint indicator soil compaction is based on the model of Stoessel et al. (2018), where long-term yield losses due to soil compaction are assessed in a regionalised manner and for different agricultural production systems. This model was developed for use in LCA.

The model allows practitioners to calculate **driving intensity** of agricultural machinery in corrected ton-km (or tkm). This represents a proxy for the cumulated pressure on the soil caused by the machinery, which is the main cause of soil compaction, during one growing cycle on 1 ha. The distance driven per ha and machine is corrected for any extra traffic that might occur on the field (e.g., turns on the head of the fields), as well as for the characteristics of the machine used (e.g., the weight on different parts of the machine) (Stoessel et al., 2018).

The model provides standard factors on driving intensity, in corrected ton-km per hectare, for a variety of common crops, such as potatoes and sugar beets, and allows for a distinction between organic and conventional production systems. For the purposes of this module only factors related to the bottom layer of the soil are considered, as the effects there are permanent and irreversible (subsoil compaction). These factors can be found in Annex C.

One should take into account that the factors given use one machine specification (i.e., working width, machine weight, and tire pressure) for the same application, e.g., harvesting, for both organic and conventional production. The difference between the two production systems comes from the number of machinery passes on the field in one growing cycle. If the researcher wants to specify the type of machinery used in the production system as part of their assessment, they should consult the original model documentation from Stoessel et al. (2018).

The driving intensity per hectare should then be converted to driving intensity per functional unit of the study (e.g., 1 kg of produce) dividing by the annual yield per hectare.

[8] In case of primary measurement, T could be changed to a shorter time interval, if more relevant. See Ogle et al. (2019a) for more details.

6.4. Data requirements

Based on the modelling approach described above, the following datapoints are needed for each process in the lifecycle where the impact of soil degradation has to be quantified.

Soil erosion

The following data are required to model water soil erosion, if no existing study is available that provides an estimate.

- erosive force of rainfall (R)
- the extent to which the type of soil erodes (K)
- the length and steepness of the slope of the area over which erosion is calculated (LS)
- the way in which the soil is used (C)
- the extent to which precautions against erosion are taken (P)

Potential sources for secondary process data related to soil erosion include the European Soils Date Centre (ESDAC, n.d.c) and the Harmonized World Soil Database (FAO, 2019).

The following data are required to quantify wind soil erosion if an estimate is not available.

- weather factor (WF)
- soil erodible fraction (EF)
- soil crust factor (SCF)
- soil roughness (K')
- combined crop factor (COG)

Potential sources for secondary process data related to soil erosion include the European Soils Date Centre (ESDAC, n.d.c).

SOC loss

The following data are required to quantify SOC loss:

- the SOC levels per hectare (top 30 cm layer), currently and 20 years before (or other relevant time interval).
- If SOC measurements are not available, these can be calculated using equation (5) in Annex B. For this, data on management systems, climate regions and soil types, reference C-stock and different stock change factors are required. Default parameters are provided by Ogle et al. (2019a) and Ogle et al. (2019b).

Location specific data and calculations may be required under two conditions: if there are locations within a value chain step with different types of climate, soil and agricultural systems or when rotation takes place. Soil degradation should then be calculated separately for each location and a weighted average should be taken. If rotation takes place, it should be included in the equation.

Soil compaction

Data required for the quantification of soil compaction are based on the crop produced. Standard factors on driving intensity for a variety of crop types are provided in Annex C. The data needs required for a more detailed assessment, based on the agricultural machinery used, can be found in Stoessel et al. (2018).

7. Monetisation

An overview of the monetisation factors for all applicable indicators of soil degradation are presented in Table 2. The economic value of soil quality is highly location specific. However, a local estimate is difficult to generalise and requires many and detailed local data points. Therefore, for soil erosion and SOC loss, it has been decided to use global average values developed for use in analysis of product chains. Location-specific characteristics that affect the true price of soil erosion and SOC loss can be applied during the quantification step (see section 6.1). If in the future more location specific monetary values for these indicators will be available, that are consistent with this methodology, their use may be preferrable.

For soil compaction, a country-specific monetisation approach is provided.

Table 2: Monetisation factors for soil degradation indicators

Indicator	Sub-indicator	Unit	Value - Global	Value - NL	Source
Soil erosion	Soil erosion (water)	EUR_{2020}/kg soil loss	0.0214	0.0214	FAO (2014)
	Soil erosion (wind)	EUR_{2020}/kg soil loss	0.0273	0.0273	FAO (2014)
SOC loss		EUR_{2020}/kg SOC loss	0.0300	0.0300	Ligthart & van Harmelen (2019)
Soil compaction		EUR_{2020}/ ton-km	0.5518	3.5440	Derived from Stoessel et al. (2018); FAOSTAT (2018a); FAOSTAT (2018b)

- The suggested monetisation approach for **soil erosion** is damage cost. Here in particular the valued damages focus on the on- and off-site components of soil erosion. They include on-site damage such as loss of nutrients, reduced harvests and reduced value of the land, and off-site damage such as the silting up of waterways, flooding and repairing public and private property. Considering the various damages mentioned above, it should be noted that this approach may overestimate the external cost. These monetisation factors derived from FAO present a global estimate.
- The suggested monetisation approach for **SOC loss** is marginal damage cost based on future crop yield loss. Although Ligthhart and Van Harmelen (2019) provide both a damage- and abatement-based shadow price, they argue in favour of using the damage-based price because there is not enough information to properly estimate the abatement value given scarce economic data. It should be noted that the damage-based value may not cover all relevant external damages related to SOC loss because it is estimated using marginal yield losses. Nevertheless, it can still serve as a conservative proxy for the chemical, physical, biological and ecological decline of soil due to loss of SOC. Moreover, the abatement cost they provide is higher than the damage cost. Since the damage is not considered severe, the lower value (damage cost) is used, following the guidelines provided in **The Valuation Framework for true price assessment of agri-food product** (Galgani et al., 2021b). For further information on this refer to Annex D. This monetisation factor is a global average.
- The suggested monetisation approach for **soil compaction** is damage cost based on lost future crop yields. The method focuses on long term soil fertility losses, which are largely irreversible. They are considered external costs as they affect the global population through land degradation, rather than only the landowner. This is explained in Section 3. Other off-site costs such as flooding, water pollution and increased GHG emissions, associated with subsoil compaction, are not

included in the monetisation factor. Flooding costs can reach up to 100% of the average production loss value, as observed in a UK case study. Currently there is no available methodology to calculate the off-site costs of subsoil compaction in a true price assessment. For more information concerning the UK case study see Annex E. The damage cost from soil compaction is calculated based on the average gross revenue of crop production lost due to irreversible subsoil compaction. This is quantified as the present value of future crop yield losses (over 100 years) due to one year of machinery use. Average yearly loss of crop yield (in %) per corrected tkm per ha over 100 years of production is provided in Stoessel et al. (2018), with country- and region-specific factors. For the Netherlands, this is 0.00166%. This factor takes into account the moisture and clay content of the soil in the region. Average value of annual gross production per hectare[9] (in EUR/ha) is estimated from data collected from FAOSTAT for all crops produced in the country (FAOSTAT, 2018a). For the Netherlands, this is estimated to be 6,655 EUR/ha at 2020 prices. Since the average yearly loss is given for 100 years of production, future crop production losses (0.12 EUR/tkm) are discounted to determine the present value, with a discount rate equal to 3% (Werkgroep discontovoet, 2015) and summed over 100 years. This results in 3.54 EUR/tkm. Countries like the Netherlands, with very high yields of crop production, will have a higher value of expected lost yields than the global average, resulting in a higher monetisation factor. The global value represents an average of all countries.

Valuation of soil degradation for the purpose of true pricing should focus on external effects only, excluding private costs which are borne by the farmer (as landowner or land manager) and therefore already reflected in production costs. In practice, there is some degree of overlap in these estimates and further research is required to fully separate private costs from societal costs. Section 3 includes a discussion of private costs and societal costs of soil degradation.

Controlling for overlap with contribution to climate change

It is important to consider the possible overlap with the contribution to climate change impact regarding the emissions of carbon previously stored in the soil. When soil erodes, the content of organic carbon that is stored in that soil is released contributing negatively to climate change. If soil carbon is not explicitly within scope in the data used for contribution to climate change, it is calculated using the SOC footprint as quantified in chapter 6.2. The monetised impact is then added to the value of climate change, where soil carbon was not within scope.

The monetisation factor that is proposed in this context is 0.55 EUR_{2020}/kg SOC loss. This is the same monetisation factor that is used for contribution to climate change, from the **Contribution to Climate Change** module (Galgani et al., 2021c), corrected for the conversion from carbon to CO_2.[10,11]

8. Limitations and items for further research

8.1. Limitations

- The FAO study that is used for monetisation of soil erosion in this module comes with its own limitations. 60% of the costs included in the study are on-site costs, mainly water runoff, nutrient

[9] Gross revenue value, as we look at lost yield with the same use of input, so lost revenue where costs will be incurred anyway.

[10] Using the marginal abatement cost of 0.152 EUR_{2020}/kg CO_2-eq as a monetisation factor (based on Kuik et al., 2009).

[11] Based on the molecular values of C and CO2, 1 tonne C equals 3.66 tonnes CO2.

loss and loss in soil depth, with off-site costs (health, landscape, recreation and others) accounting for the remaining ones. These costs are based on replacement costs from a 1992 study, with prices (like energy prices) not being updated and without any averaging across types of land. Moreover, local estimates are not part of the scope of the study, while soil quality is highly location specific. Ideally, valuation based on local data should be applied. Still, the study was chosen since it is one of the only large reviews realised until now, and the most recent one on the costs of soil erosion worldwide.

- Damage from SOC loss in monetary terms will vary from region to region. The method only uses a global average, like for soil erosion. This is based on a reliable literature review; however, a location specific value would be preferable.
- External costs of soil compaction are based on yield loss. Flooding, greenhouse gas emissions (nitrous oxide emissions) and water pollution are also important effects. These are hard to estimate and it is unclear to what extent they are relevant to countries like the Netherlands. Runoff of minerals, which leads to water pollution, may be very relevant in the neighbourhood of nature areas, even though this cost is included at the moment as part of water pollution, but not as part of soil compaction.
- The importance of soil compaction varies per region, with different effects taking place, also within the same country. The estimation method provided in true pricing is still rough and should be adjusted to account for local conditions as well. Moreover, the soil compaction method adopted in this module gives standard values for standard management practices. In case some of the measures to reduce soil compaction are implemented, these values should be reduced. Causalities are however not well-known. Search for standard numbers is still needed.
- The productivity effects of soil compaction can be considered internal costs, as it has consequences on the land farmers work on. However, in practice, land prices are often not related to soil quality. Therefore, it is probably not included in the market price and it can be considered external.
- While it is possible to distinguish between different farm management choices, to account for the impact of soil compaction (see section 6.3 on machinery passes on the field in one growing cycle), this can be a complex calculation. It is therefore recommended that this approach should be applied to cases that soil compaction is of high materiality. For all other occasions the default values presented in this document can be used.
- As mentioned previously, the monetisation approach for each soil degradation indicator is damage cost, which includes both private and societal cost. Separation between these types of costs is particularly difficult to achieve. Private costs can result in increased product prices and ultimately lower land prices. Still, regarding food security, the damage applies to everyone.

8.2. Items for further development

- Selection of the agricultural processes and sectors that contribute the most to soil degradation (‘high materiality’ processes and sectors).
- Improve ease of use of modelling approaches and data sources for estimating the selected footprint indicators.
- Further guidance on the ways to quantify wind erosion could be provided in the future.
- Further in-depth study to account for the off-site costs of soil compaction (flooding, water pollution, etc.).

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Annex A. Correction for SOC lost due to erosion

This annex briefly discusses when SOC loss should be corrected with regards to erosion and it provides the equation that can be used to make the correction.

SOC is also lost when the soil is eroded. To prevent this from leading to double counting in the calculation of external costs, the SOC loss due to soil erosion must be deducted from the SOC loss footprint. To do this, the average SOC content per ha is converted to SOC per kg soil:

(3) $$SOC_{content} = \frac{\frac{SOC_{T/2}}{d}}{\rho}$$

Where:

$SOC_{content}$ is the soil organic content per kg soil (kg C / kg soil).

$SOC_{T/2}$ is the average content of SOC per unit area: (SOC_0 + $SOC_{0\text{-}T}$)/2 (converted from kg/ha to kg/m^2).

d is the depth of the SOC measurement in the soil (in m). 0.3 m is the default value. If an alternative value is used, this should be substantiated.

ρ is the density of the soil (in kg/m^3). Use a local value, for example the average for the type of soil.

The value of SOC content is multiplied by the footprint for soil erosion and subtracted from the footprint for SOC loss:

(4) $$SOC_{loss,corr} = SOC_{loss} - soil\ loss * SOC_{content}$$

Where:

$SOC_{loss,corr}$ is the loss of soil organic content corrected for soil erosion (in kg.ha^{-1}.yr^{-1}).

SOC_{loss} is the loss of soil organic content without correction for soil erosion (in kg.ha^{-1}.yr^{-1}).

$soil\ loss$ is the loss of soil in kg.$ha^{-1}yr^{-1}$.

Annex B. Quantifying SOC loss with the carbon stock equation

As mentioned in Section 6, the difference in C stocks can be calculated according to the IPCC equation (Ogle et al., 2019a). The equation can be used when existing SOC measurements are not readily available. The calculation of SOC_0 and $SOC_{0\text{-}T}$ consists of a reference C-stock for a given climate and soil type class, corrected for factors relating to the type of land use, the way in which the land is managed, the organic inputs that are used and the land area being estimated. The equation is given below (Ogle et al., 2019a, pp 33, equation 2.25[12]):

(5) $$SOC = \sum_{c,s,i}(SOC_{REF_{c,s,i}} * F_{LU_{c,s,i}} * F_{MG_{c,s,i}} * F_{I_{c,s,i}})$$

Where:

- c represents the climate zones, s the soil types, and i the set of management systems that are present in a country.
- SOC_{REF} is the reference carbon stock, in tonnes C per ha.
- F_{LU} is the stock change factor for land-use systems or sub-system for a particular land use (dimensionless). Examples of land-use systems of sub-systems are long-term land use for cultivation purposes, long-term perennial tree crops such as fruit and nut trees, coffee and cacao, long-term annual cropping of wetlands or temporary set aside of annually cropland (e.g., conservation reserves).
- F_{MG} is the stock change factor for management regime (dimensionless). Examples of management regimes include different tillage practices in cropland (full, reduced and no tillage).
- F_I is the stock change factor for input of organic matter (dimensionless). This factor represents the different levels of carbon input in the soil (low, medium, high with and without manure). For example, a low input level can occur by the removal of crop residues or through the production of crops yielding low residues (e.g., vegetables, tobacco, cotton).

Equation (5) computes the change in organic C stock (SOC) for 1 hectare. This is done by calculating the organic C stock remaining after a management change, relative to the organic C stock in a reference condition, and summing this change over all climate zones, soil types and management practices included in the inventory.

The IPCC guidelines provide three approaches with increasing level of detail (Tiers 1 to 3) (Ogle et al, 2019a). Tier 1 is the basic calculation as described above with standard factors for SOC_{REF}, F_{LU}, F_{MG} and F_1, specified on climate, soil type and land management system. Tier 2 involves the use of country-specific factors with the same equation. Tier 3 includes more complex models that consider interaction between factors, which often also requires periodically collected primary data. Tier 3 is out of scope in this module.

Tier 1

Inventory calculations for Tier 1 are based on land areas that are stratified by climate regions and default soil types. Soil organic C stocks are computed to a default depth of 30 cm, while the reference condition is defined as that present in native lands (i.e., non-degraded, unimproved lands under native vegetation) for the default reference soil organic C stocks (SOC_{REF}).

Default soil types and the corresponding reference carbon stock SOC_{REF} can be seen in Table 3. Default values for F_{LU}, F_{MG} and F_I for Tier 1 can be found in Chapter 5 of the 2019 IPCC report, pages 27-28, Table 5.5 (Updated) (Ogle et al., 2019b).

[12] In the original equation a factor A was also included (Area to be assessed). Here it is removed since we describe the formula to be used for 1 ha of land.

Tier 2

A Tier 2 approach is a natural extension of the Tier 1 method that allows an inventory to incorporate country specific data. Tier 2 incorporates the same equation and methodological steps as Tier 1. According to IPCC, *'It is good practice for countries to use a Tier 2 approach, if possible, even if they are only able to better specify certain components of the Tier 1 default approach*' (Ogle et al., 2019a). For example, it is possible to use the Tier 2 approach, if the only country-specific data available concern reference C stocks. These can then be used with default factors (Ogle et al., 2019b, Table 5.5 (Updated)) to estimate changes in soil organic C stocks.

Country-specific data can be used to improve four components when applying equation (5) for estimating stock changes in soils. The components include **a) derivation of region or country-specific stock change factors**, **b) reference condition C stocks**, **c) specification of management systems**, and/or d) **classification of climate and soil categories** (Ogle et al., 2019a). Inventories with country -specific data can be complied for all of these components or any subset of these, combined with default values presented in Tier 1. Application of this method can generate SOC stock change factor that are specific to climate, soil and management. Additional information on how to derive country-specific data on these four components can be found in Chapter 2 of the 2019 IPCC report, pages 38-42 (Ogle et al., 2019a).

For inventory compilers who have access to any country-specific data concerning the four components mentioned above, it is recommend to use the Tier 2 calculation. For components for which no specific data are available, default values (as presented in Tier 1) can be used.

Table 3: Default (mean) reference Soil Organic C-stocks (SOC_{REF}) for mineral soils (tonnes C per ha in 0-30 cm depth). NO: soil type does not normally occur within the climate zone. Source: Ogle et al. (2019a).

IPCC Climate zone	**IPCC soil class**		
	High Activity Clay soils	**Low Activity Clay soils**	**Sandy soils**
Polar Moist/Dry	59	NA	27
Boreal Moist/Dry	63	NA	10
Cool temperate dry	43	33	13
Cool temperate moist	81	76	51
Warm temperate dry	24	19	10
Warm temperate moist	64	55	36
Tropical dry	21	19	9
Tropical moist	40	38	27
Tropical wet	60	52	46
Tropical montane	51	44	52
	Spodic soils	**Volcanic soils**	**Wetland soils**
Polar Moist/Dry	NO	NA	NA
Boreal Moist/Dry	117	20	116
Cool temperate dry	NO	20	87
Cool temperate moist	128	136	128
Warm temperate dry	NO	84	74
Warm temperate moist	143	138	135
Tropical dry	NA	50	22
Tropical moist	NA	70	68
Tropical wet	NA	77	49
Tropical montane	NA	96	82

Annex C: Factors for quantifying soil compaction for common crops

Table 4 shows the driving intensity values for common crops in (corrected) tkm per ha. Tkm per ha is used as a proxy for the pressure on soil, that subsequently translates into compaction damage. The differences between organic and integrated crop farming are partly due to the number of machinery that passes during one growing cycle. Fertiliser and pesticide application differences between regimes result in a different number of passes. Another factor that affects the driving intensity of the different crops is the working widths of the machine types used. This is more evident in the machines used for application of farmyard manure in organic systems versus disc spreaders used for synthesised fertilisers, and in the mechanical weeding in organic agriculture versus the application of pesticides in conventional farming (Stoessel et al., 2018).

Table 4: Driving intensity values for common crops (in (corrected) tkm/ha). OeLN = conventional (Swiss standard). Source: Stoessel et al. (2018).

Crop	Crop name in model	Bottom soil layer
Corncob mix	Corncob mix, OeLN intensive, from field	24.6
Corncob mix	Corncob mix, OeLN, from field	28.6
Corncob mix	Corncob mix, organic, from field	34.3
Fava beans	Fava beans, OeLN intensive, wholesale	24.6
Fava beans	Fava beans, OeLN, wholesale	24.6
Fava beans	Fava beans, organic, wholesale	30.3
Fodder beet	Fodder beet, OeLN intensive, wholesale	24.4
Fodder beet	Fodder beet, OeLN, wholesale	28.4
Fodder beet	Fodder beet, organic, wholesale	34.1
Grain maize	Grain maize, OeLN intensive, wholesale	24.6
Grain maize	Grain maize, OeLN, wholesale	28.6
Grain maize	Grain maize, organic, wholesale	34.3
Machine beans	Machine beans, OeLN	3.6
Machine beans	Machine beans, organic	3.9
Meadow forage	Meadow forage, OeLN intensive, sale	39.8
Meadow forage	Meadow forage, OeLN, sale	44.3
Meadow forage	Meadow forage, organic, sale	50.3
Meadow	Meadow, OeLN	46.3
Meadow	Meadow, OeLN intensive	45.8
Meadow	Meadow, organic	50.3
Oat	Oat, OeLN extensive, retail	34.0
Oat	Oat, organic, retail	43.7
Potatoes	Potatoes, OeLN intensive, wholesale	65.6
Potatoes	Potatoes, OeLN, wholesale	69.6
Potatoes	Potatoes, organic, wholesale	75.3
Protein peas	Protein peas, OeLN intensive, wholesale	24.6
Protein peas	Protein peas, OeLN, wholesale	24.6
Protein peas	Protein peas, organic, wholesale	30.3
Rapeseed	Rapeseed, OeLN intensive, wholesale	24.6
Rapeseed	Rapeseed, OeLN, wholesale	28.6

Crop	Crop name in model	Bottom soil layer
Rapeseed	Rapeseed, organic, wholesale	34.3
Rye	Rye, OeLN extensive, wholesale	34.0
Rye	Rye, OeLN intensive, wholesale	30.0
Rye	Rye, organic, wholesale	43.7
Silage maize	Silage maize, OeLN intensive, standing from field	38.8
Silage maize	Silage maize, OeLN, standing from field	42.8
Silage maize	Silage maize, organic, standing from field	48.5
Soy	Soy, OeLN intensive, wholesale	24.6
Soy	Soy, OeLN, wholesale	24.6
Soy	Soy, organic, wholesale	30.3
Spelt	Spelt, OeLN extensive, wholesale	34.0
Spelt	Spelt, OeLN intensive, wholesale	30.0
Spelt	Spelt, organic, wholesale	43.7
Sugar beet	Sugar beet, OeLN intensive, wholesale	11.0
Sugar beet	Sugar beet, OeLN, wholesale	15.0
Sugar beet	Sugar beet, organic, wholesale	20.7
Summer oat	Summer oat, OeLN extensive, wholesale	34.0
Summer oat	Summer oat, OeLN intensive, wholesale	30.0
Summer oat	Summer oat, organic, wholesale	43.7
Summer wheat	Summer wheat TOP, OeLN extensive, wholesale	34.0
Summer wheat	Summer wheat TOP, OeLN intensive, wholesale	30.0
Summer wheat	Summer wheat TOP, organic, wholesale	43.7
Sunflower	Sunflower, OeLN intensive, wholesale	24.6
Sunflower	Sunflower, OeLN, wholesale	28.6
Sunflower	Sunflower, organic, wholesale	34.3
Threshing peas	Threshing peas, OeLN	3.6
Threshing peas	Threshing peas, organic	3.9
Tobacco (1)	Tobacco, Burley, OeLN, air dried	13.0
Tobacco (2)	Tobacco, Virgine, OeLN, air dried	13.0
Triticale	Triticale, OeLN extensive, wholesale	34.0
Triticale	Triticale, OeLN intensive, wholesale	30.0
Triticale	Triticale, organic, wholesale	43.7
Winter barley	Winter barley, OeLN extensive, wholesale	34.0
Winter barley	Winter barley, OeLN intensive, wholesale	30.0
Winter barley	Winter barley, organic, wholesale	43.7
Winter wheat	Winter wheat TOP, OeLN extensive, wholesale	34.0
Winter wheat	Winter wheat TOP, OeLN intensive, wholesale	30.0
Winter wheat	Winter wheat TOP, organic, wholesale	43.7

Annex D: Supplementary information about monetisation

This chapter compares the use of marginal damage cost over marginal abatement cost and provides the main reasons for choosing the selected sources.

D.1. Damage and abatement cost for soil erosion and SOC loss

Section 7 of this document discuss the valuation approaches of soil erosion and SOC loss, respectively. For soil erosion we propose to use damage cost to monetise soil loss, in particular the value of 0.0273 EUR_{2020}/kg soil loss as proposed by FAO (2014). For SOC loss we propose to use the damage cost value of 0.030 EUR_{2020}/kg SOC lost to monetise SOC loss.

An alternative would be to use the abatement cost of soil erosion and SOC loss. For soil erosion, this reflects the costs of soil management practices to prevent soil erosion from occurring beyond a certain target and of restoring eroded land. For SOC loss, the abatement-based value provides an estimate of the costs of measures required to reduce the loss of SOC due to agricultural land use either by direct application of organic carbon or by indirect management practices (‘restoration’).

Damage cost is chosen over abatement (or restoration) cost in line with the true price valuation framework. The remediation philosophy of true pricing states that when harm is not severe and restoration has a higher price than compensation to people damaged (i.e., the damage costs), damage cost is the preferred monetisation approach. These criteria are indeed met. That damage is not severe follows from the fact that there are no clear overshoots of planetary boundaries related to soil degradation (Robèrt et al., 2013), and that most of the damage is indirect.

That restoration has a higher price than compensation to people damaged (i.e., the damage costs) is shown for SOC loss in Table 5. For soil erosion, the authors have not found a high-quality source providing a restoration value.

Table 5: Suggested monetization factor for SOC loss and associated source

Suggested source	Value in Euro, price level 2014	Value in Euro, price level 2020
Ligthart & Van Harmelen (2019)		
Damage = compensation	0.029 EUR_{2014}/kg SOC loss	0.030 EUR_{2020}/kg SOC loss
Abatement = restoration	0.100 EUR_{2014}/kg SOC loss	0.105 EUR_{2020}/kg SOC loss

A final note on not using restoration refers to the degree to which soil degradation is also an internal effect. Restoration is primarily the responsibility of the landowner, but should they fail to do so, *external damages* occur.

D.2. Reasons for chosen specific sources

The study by FAO is chosen for four main reasons, listed in Table 6.

Table 6: Reasons for selecting FAO (2014)

#	Reason
1.	FAO presents a global estimate. The economic value of soil quality is highly location specific. A local estimate is difficult to generalise and requires many and detailed local data points. Therefore, it has been decided to use global values developed for use in analysis of product chains.

2.	This study is based on a thorough review of available evidence on the cost of erosion and it is relatively recent.
3.	The FAO is cited and acknowledged by other important actors within the field of land, food, and climate studies (e.g., Lal (2009); Mann (2002); Sanchez (2002)).
4.	The FAO is a well-known and respected organisation.
	Potential downside of the study
1.	The generalisation of a global estimate to a location-specific situation may cause biased results.

The study by Lighthart & van Harmelen (2019) is chosen for three reasons, listed in Table 7.

Table 7: Reasons for selecting Ligthart & van Harmelen 2019

#	Reason
1.	To the best of the authors' knowledge, it is one of the few meta-analyses that provide economic values of SOC loss.
2.	It is developed for use in LCA by researchers at TNO and Wageningen University.
3.	It contains both a damage-based and abatement-based value for SOC loss.
	Potential downside of the study
1.	The quality of the estimated shadow prices is limited, because they are derived for impacts where economic data is relatively scarce.

Annex E: Case study on off-site soil compaction costs

Graves et al. (2015) assessed '*how degradation affects the capacity of soils to support a range of 'final goods', distinguishing between on-site and off-site costs, and market and non-market effects´*. The effects and related economic costs of soil compaction are included in their research, which covers England and Wales.

On-site costs of compaction in this study consist of:

- private costs due to yield reduction (both in agriculture and forestry).
- the private costs of extra draught power (associated to ploughing and cultivation operations).
- the private costs of nutrient loss (N, P and K) due to the extra water runoff.

Estimates on yield losses were based on literature and expert opinion.

Off-site costs include:

- the additional deposition of the lost nutrients in the water environment. The costs of water pollution include the cost of water treatment and damage to the water environment.
- the additional flooding associated with water runoff.
- GHG emissions[13] connected to the extra draught power required to manage topsoil compaction and the additional fertiliser used to recover for the lost nutrients.

The estimated total cost of compaction is £472 million per year, about half of which are on-site costs and half off-site costs.

The majority of off-site costs assessed in this case study are connected to flood damage and flood risk management costs. Graves et al. (2015) stated that '*agricultural intensification has been associated with increased flood probability, and that appropriate land management to "retain water in the landscape" could contribute to flood risk mitigation*'. They estimate that 3-10% of the total flood damage and flood mitigation costs that occur in England and Wales annually, can be attributed to soil compaction. This estimation is based on the assumption that changes in the soil condition affect the depth of run-off and are associated with an equivalent change in the probability of flooding.

Graves et al. (2015) noted that the estimated total annual costs of soil compaction are '*nearly three times greater than those of erosion, reflecting its greater occurrence in the landscape and effect on society'*. An overview of the total costs estimated can be seen in Table 8.

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[13] From Graves et al. (2015): '*The use of diesel and fertilisers is associated with a range of GHG related burdens. The global warming potential (GWP) of diesel includes the CO2-eq involved in producing and using diesel in field operations, whilst the N, P and K values include CO2-eq for producing fertilisers. The environmental burdens were calculated in relation to the additional use of diesel and nutrients needed to compensate for the effects of compaction.*'

Table 8: Estimated cost of soil compaction in England and Wales. Table from Graves et al. (2015), p. 408.

Estimated cost (£'000) of soil compaction in England and Wales (E&W) — all soilscapes.

Data category	Data description	Data value	unit
Physical data			
Area at risk of compaction	Total areas at risk within categories	3,858,670	ha
Physical losses of fertiliser	Fertiliser N loss	37,044	$t\,a^{-1}$
	Fertiliser P loss	979	$t\,a^{-1}$
	Fertiliser K loss	1,751	$t\,a^{-1}$
Added traction	Additional diesel use	41,611,174	$l\,a^{-1}$
On-site costs			
Provisioning service	Crop productivity and production loss	161,670	£'000
	N fertiliser loss	22,697	£'000
	P fertiliser loss	666	£'000
	K fertiliser loss	911	£'000
	Additional diesel use	17,477	£'000
Off-site costs			
Drinking water quality service	N in drinking water	2,166	£'000
Environmental water quality service	N in rivers and lakes	2,028	£'000
	N in transitional waters	112	£'000
	P in freshwater lakes	1,377	£'000
Flood regulation service	Flooding damage cost	168,000	£'000
Climate regulation service	GHG cost of N as N_2O	73,627	£'000
	GHG cost of N as NH_3	3,458	£'000
	GHG cost of increased N loss	9,446	£'000
	GHG cost of increased P loss	50	£'000
	GHG cost of increased K loss	45	£'000
	GHG cost of additional diesel	6,579	£'000
Total costs			
	Total on-site cost	203,691	£'000
	Total off-site cost	266,889	£'000

Annex F. The right to a safe, clean, healthy, and sustainable environment and the right to have access to the natural resources of the earth (for future generations) in international conventions

Soil degradation is related to *the right to a safe, clean, healthy, and sustainable environment* and *the right to have access to natural resources of the earth (for future generations)*. This annex shows how this is represented in various international conventions. Soil fertility is considered a renewable natural resource and a fertile soil is considered part of a sustainable environment.

For a complete (preliminary) list of a list of rights, principles, and obligations relevant to true pricing, please refer to the **Principles of True Pricing** (True Price Foundation, 2020).

The right to a safe, clean, healthy, and sustainable environment

General

- States should ensure a safe, clean, healthy, and sustainable environment in order to respect, protect and fulfil human rights. - *Framework principles on human rights and the environment, United Nations Human Rights special procedures, 2018 (principle 1)* (UN Human Rights Special Procedures, 2018)

- The impact of climate change, the unsustainable management and use of natural resources, the unsound management of chemicals and waste, the resulting loss of biodiversity and the decline in services provided by ecosystems may interfere with the enjoyment of a safe, clean, healthy and sustainable environment, and that environmental damage can have negative implications, both direct and indirect, for the effective enjoyment of all human rights. *Resolution adopted by the Human Rights Council on 22 March 2018 37/8. Human rights and the environment* (UN General Assembly, 2018)

- More than 100 States have recognized some form of a right to a healthy environment in, inter alia, international agreements, their constitutions, legislation or policies. *Resolution adopted by the Human Rights Council on 22 March 2018 37/8. Human rights and the environment* (UN General Assembly, 2018)

Specifically with regards to the effects of degradation of land, biodiversity and ecosystems

- "Man has a special responsibility to safeguard and wisely manage the heritage of wildlife and its habitat." - *Declaration of the United Nations Conference on the Human Environment, Stockholm, 1972 (principle 4)* (UN, 1972)

- Renewable resources […] need not be depleted provided the rate of use is within the limits of regeneration and natural growth. - *Our Common Future, World Commission on Environment and Development, 1987 (The concept of sustainable development)* (Brundtland, 1987)

- "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss." – *Sustainable development goal 15* (UN, 2015)

The right to have access to the natural resources of the earth (for future generations)

- The natural resources of the earth must be safeguarded for the benefit of present and future generations. - *Declaration of the United Nations Conference on the Human Environment, Stockholm, 1972 (principle 2)* (UN, 1972)

- "The non-renewable resources of the earth must be employed in such a way as to guard against the danger of their future exhaustion and to ensure that benefits from such employment are shared by all mankind." - *Declaration of the United Nations Conference on the Human Environment, Stockholm, 1972 (principle 5)* (UN, 1972)

- "The rate of depletion [for non-renewable resources] should take into account the criticality of that resource, the availability of technologies for minimizing depletion, and the likelihood of substitutes being available." - *Our Common Future, World Commission on Environment and Development, 1987 (The concept of sustainable development)* (Brundtland, 1987)

Glossary

Soil compaction	Natural and machinery induce process, where soil volume decreases affecting the soil pore functions.
Soil erosion	Natural process by which factors such as water, wind and gravity erode soil. This process can be influenced by anthropogenic activities.
SOC (soil organic carbon)	Soil Organic Carbon (SOC) refers to the carbon content of soil organic matter (SOM).
SOM (soil organic matter)	All material in the soil that is produced by living organisms (plants or animals) and ends up in the soil through decomposition (Bot, 2005).